# Tensor Reggeons from Warped Space at the LHC

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Maxim Perelstein[1] Andrew P. Spray[2]

[1]Cornell University, Ithaca NY

[2]TRIUMF, Canada

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# Title Explanation

## Tensor Reggeons from Warped Space at the LHC

- Tensor means Spin 2 particles;
- Reggeons means String-inspired;
- Warped means Randall-Sundrum;
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# Outline

# TeV-Scale Gravity

There are two different conceptions of the traditional Hierarchy Problem. They lead to two different types of solution:

- Why is $\Lambda_{SM}$ so small? $\longrightarrow$ Raise cut-off scale.
  - Supersymmetry, Little Higgs Theories, Technicolour, ...
- Why is $M_{Pl}$ so large? $\longrightarrow$ Lower scale of gravity.
  - Large Extra Dimensions (Arkani-Hamed, Dimopoulos & Dvali models)
  - Warped Extra Dimensions (Randall-Sundrum models)

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# Quantum Gravity at the LHC

TeV-scale gravity as an effective field theory:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_n \frac{c_n}{(M_{grav})^n} \mathcal{O}_n .$$

For $E \gtrsim M_{grav}$, we need to know all the $c_n$!

We need the UV completion;
but the cupboard of quantum gravity is pretty bare.

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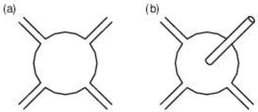
# String Theory at the LHC
## The Usual Approach

String Theory at the LHC has been looked at previously:

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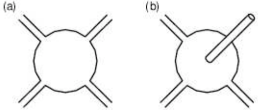


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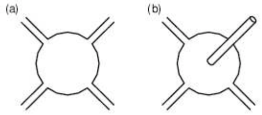


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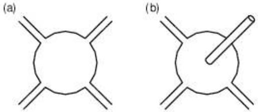


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Unfortunately, String Theory in RS not currently calculable. :(

(See Reece, Wang: 1003.5669[hep-ph]).

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2. Construct flat-space EFT to describe them.
3. Covariantly generalise EFT to RS.
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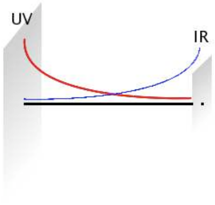
# Randall-Sundrum: A Refresher and Notation

RS Models are 5D orbifolds with a non-trivial warped geometry.

$$\mathrm{d}s^2 = \mathrm{e}^{-2k|y|}\,\mathrm{d}x^\mu \mathrm{d}x_\mu - \mathrm{d}y^2; \qquad y \sim -y.$$

Define IR scale $\Lambda_{IR} \equiv k\,\mathrm{e}^{-k\pi R}$.
UV Scales: $k \ll M_S \ll M_{Pl}$; $k \sim M_{Pl}/10$.




- SM states are zero modes of five dimensional fields;
- First “Higgsed” Model:
  - $\Lambda_{IR} \sim 1$ TeV;
  - Fermions are localised in XD.
- Second “Higgsless” Model
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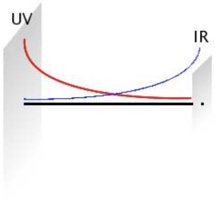


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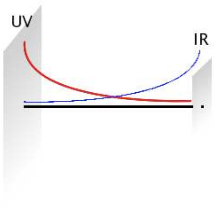


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# Regge Resonances in Flat Space

General result in flat space:

$$\mathcal{A}_{str} \sim \mathcal{A}_{SM} \times \mathcal{S}(s,t).$$

$\mathcal{S}(s,t)$ is Veneziano amplitude:

$$\mathcal{S}(s,t) = \frac{\Gamma(1-\alpha' s)\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s-\alpha' t)}.$$

This has infinite set of poles at $\alpha' s = n$ for $n \geq 1$.

Near $n$th pole, can reproduce string amplitudes with particles of mass $n/\alpha' \equiv nM_S^2$.

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# Regge Resonances in Flat Space II

Cullen, Peskin & Perelstein, hep-ph/0001166.

In 4d flat space Stringy QED, find at $n = 1$:

- One spin two state;
- One vector state;
- Several Scalars.

First state is most interesting:

Unusually high spin.

All interactions determined by:

- Gauge coupling $e$;
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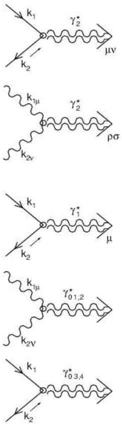

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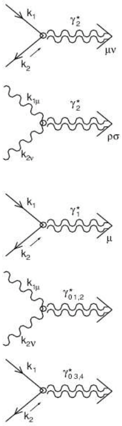

# Regge Resonances in Curved Space

Effective Theory of Spin-2 Gluon Partner:

$$\mathcal{L} = \mathcal{L}_{free} + \frac{g_s}{\sqrt{2}M_S}\left(F^{\mu\rho}F_{\rho}{}^{\nu} - \frac{1}{4}F^{\rho\sigma}F_{\rho\sigma}\eta^{\mu\nu}\right)B_{\mu\nu} + \frac{ig_s}{\sqrt{2}M_S}\left(\partial_\mu\bar{Q}\gamma_\nu q - \bar{Q}\gamma_\nu\partial_\mu q\right)B^{\mu\nu}.$$

To produce our 'RS String Model' we take the above and:

- Extend to 5D (trivial);
- Covariantly generalise (tricky);
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# Massive Spin-2 Fields in RS

## A Small Digression

In flat space:

$$\mathcal{L} = \frac{1}{4} H_{\mu\nu\rho} H^{\mu\nu\rho} - \frac{1}{2} H_{\mu\nu}{}^{\nu} H^{\mu\rho}{}_{\rho} + \frac{1}{2} m^2 \left( (B_{\mu}{}^{\mu})^2 - B_{\mu\nu} B^{\mu\nu} \right).$$

Field Strength Tensor:

$$H_{\mu\nu\rho} \equiv \partial_{\mu} B_{\nu\rho} - \partial_{\nu} B_{\mu\rho}.$$

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Correct generalisation to RS space is non-trivial:

$$\eta_{\mu\nu} \to g_{MN}; \qquad \partial_\mu \to \nabla_M; \qquad B_{\mu\nu}(y) = B_{\mu\nu}(-y);$$

$$\Delta\mathcal{L} = \frac{3}{2}k^2\Big((B_M{}^M)^2 - B_{MN}B^{MN}\Big) - k\,\partial_y\,\mathrm{sgn}(y)\Big((B_\mu{}^\mu)^2 - B_{\mu\nu}B^{\mu\nu}\Big).$$

The last term comes from expanding the Einstein-Hilbert action.

# Four-Dimensional Decomposition

Have now produced our 5D "String" theory. So the question is:

What are the 4D physics?

States we expect:

$$B_{\mu\nu} \rightarrow \text{4D Spin 2}; \qquad B_{\mu y} \rightarrow \text{4D Spin 1}; \qquad B_{yy} \rightarrow \text{4D Spin 0}.$$

Continue to focus on Spin 2 state:

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Note: Scalar also even under orbifold symmetry;
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# Eliminating Mixing Terms

Problem: $B_{\mu\nu}$ contains vector, scalar components:

$$B_{\mu\nu} \sim B_{\mu\nu}^{(n)} + (\partial_\mu A_\nu^{(n)} + \partial_\nu A_\mu^{(n)}) + \ldots$$

Equivalently, the action is not diagonal from the 4D perspective:

$$\mathcal{L} \supset \partial_\mu B^{\mu\nu}\, \partial_y B_{y\nu}.$$

Solution: Two different methods, lead to same result.

1. Add pions to restore gauge invariance;
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# The KK Spectrum I

## Equation of Motion

So, isolating the tensor components of the free action:

$$\mathcal{L}_{4D} = \int \mathrm{d}y \Big[ \mathrm{e}^{2k|y|} \left( \frac{1}{4} H_{\lambda\mu\nu} H^{\lambda\mu\nu} - \frac{1}{2} H^{\lambda\mu}{}_{\mu} H_{\lambda\nu}{}^{\nu} \right) + \frac{1}{2} B_{\mu}{}^{\mu} \mathcal{D} B_{\nu}{}^{\nu} - \frac{1}{2} B_{\mu\nu} \mathcal{D} B^{\mu\nu} \Big].$$

The mass operator $\mathcal{D}$ is

$$\mathcal{D} \equiv -\partial_y^2 + 4k^2 + m^2 - 2k\, \partial_y \, \mathrm{sgn}(y).$$

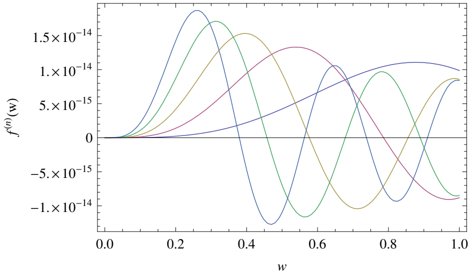
Note: Eigenvalue equation is

$$\mathcal{D} f^{(n)} = {\mu^{(n)}}^2 \mathrm{e}^{2k|y|} f^{(n)},$$

with $\partial_y(\mathrm{e}^{2k|y|} f^{(n)})$ continuous at the boundaries.

# The KK Spectrum II
## KK Functions

The solutions for $f^{(n)}$ are Bessel functions:




$$f^{(n)}(y) = \frac{1}{N}\left\{J_\nu\left(\frac{\mu^{(n)}}{\Lambda_{IR}}w\right) + c\,J_{-\nu}\left(\frac{\mu^{(n)}}{\Lambda_{IR}}w\right)\right\};$$

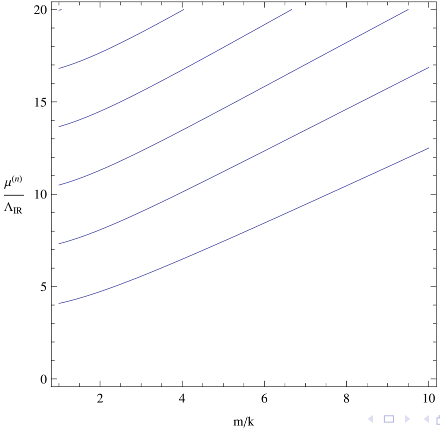
$$w = \mathrm{e}^{k(|y|-\pi R)} \in [\mathrm{e}^{-k\pi R}, 1],$$

$$\nu \equiv \sqrt{4+\mathfrak{m}^2};$$

$$N \sim \frac{\mathrm{e}^{k\pi R}}{\sqrt{k\pi R}};\ c \sim \mathrm{e}^{-2\nu k\pi R}.$$

# The KK Spectrum III
## Reggeon Masses

The Lightest Reggeon has mass (a few) $\times \frac{m}{k}\Lambda_{IR}$:



# Reggeon-Standard Model Interactions

In 4D theory, all interactions have flat space form.

Only difference is Overlap Integral.

Example: Quark-Quark-Reggeon coupling,

$$\mathcal{L}_{q\bar{q}g^*} = \sum_n \frac{i g_s \tilde{g}_i^{(n)}}{\sqrt{2}\tilde{M}_S} \left( \partial^\mu \bar{q} \gamma^\nu \tilde{B}_{\mu\nu} q - \bar{q} \gamma^\nu \tilde{B}_{\mu\nu} \partial^\mu q \right).$$

$\tilde{M}_S$ is warped-down string scale:

$$\tilde{M}_S = \mathrm{e}^{-k\pi R} M_S \sim \text{a few TeV},$$

while $\tilde{g}_i^{(n)}$ is KK wavefunction integral:

$$\tilde{g}_i^{(n)} = \mathrm{e}^{-k\pi R} \int_0^{\pi R} \mathrm{d}y \, \mathrm{e}^{-k|y|} f^{(n)} Q_i^{(0)\,2}.$$

# Overlap Integrals

Table of effective couplings:

| $\frac{m}{k}$ | $\frac{\mu^{(0)}}{\Lambda_{\mathrm{IR}}}$ | $\tilde{g}_{\mathrm{Glu}}$ | $\tilde{g}^{(0)}(c=0.65)$ | $\tilde{g}^{(0)}(c=0.5)$ | $\tilde{g}^{(0)}(c=0)$ |
|---|---|---|---|---|---|
| 2.0 | 4.72 | 0.110 | $3.9\times10^{-5}$ | 0.110 | 2.9 |
| 3.0 | 5.56 | 0.107 | $3.8\times10^{-5}$ | 0.107 | 2.9 |
| 4.0 | 6.48 | 0.104 | $3.7\times10^{-5}$ | 0.104 | 2.9 |
| 5.0 | 7.45 | 0.100 | $3.5\times10^{-5}$ | 0.100 | 2.8 |

# Cross Sections and Decay Rates

Figure: Production Cross Section

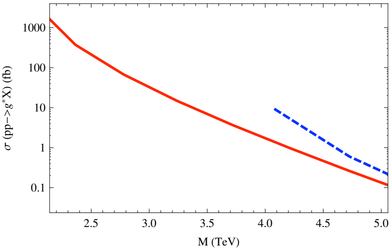
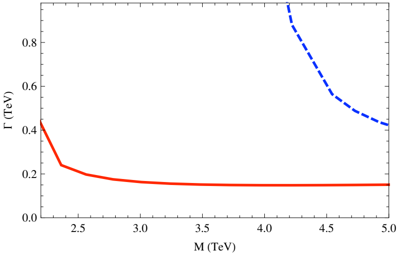


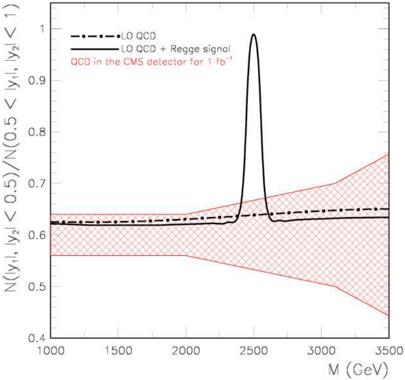

Figure: Decay Width (to SM)




Red Lines: Higgsless Model. Blue Lines: Higgsed Model.
Branching fraction over 95% to Top Quarks.

# A Proper Collider Study

A follow-up paper by Anchordoqui *et. al.* looked at detection prospects: [arXiv:1006.3044]



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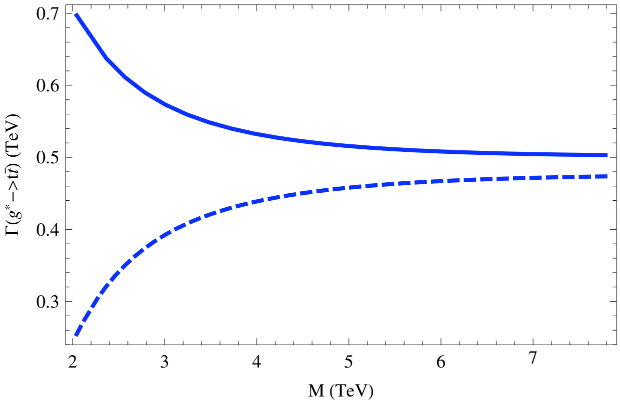
Reggeon has spin 2.

$\Longrightarrow$ Measure spin, either Reggeon or KK Graviton.

Doubly hadronic top decays allow "full" reconstruction of momentum, measure spin from this.

# New Decay Modes

All studies so far have considered decays to SM ONLY.
Decays to other RS states possible (KK excitations).



# Summary & Conclusions

1. RS models imply Stringy physics at the LHC;
2. We have constructed a string-inspired Reggeon model;
3. We expect up to 1000s of Reggeons at the LHC;
4. We hope to identify the Reggeons via cascade decays.